HOT STARS: SIX YEARS OF PROGRESS

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ABSTRACT

Mass loss is known to take place across the H-R diagram, but nowhere is it more pronounced than in the upper left hand corner of that figure. Here, winds from luminous stars peel away a solar mass in a million years or less. The winds of the Of, OB supergiants, and W-R stars have received the most attention because they are so readily studied. Their effect on stellar evolution is significant also. On the other hand, it is the B stars whose variability has been most thoroughly studied with IUE, undoubtedly because historically these stars have been known to vary. This review will concentrate on the current state of our observational understanding of stellar winds, with particular emphasis on how the observations fit various theoretical predictions.

INTRODUCTION

Early rocket observations of hot stars revealed the presence of high ionization stages such as O VI and N V, which are not expected in radiative equilibrium in O and B stars as they require temperatures greater than 10^5 K, compared with photospheric temperatures of 30,000 to 50,000 K. Furthermore, the blue edges of P Cygni profiles revealed terminal velocities greatly in excess of the stellar escape velocity, indicating mass loss (Morton 1967). Thus began the era of stellar winds in hot stars. IUE allows us to observe ultraviolet resonance lines of ions such as C IV, N V and Si IV and these lines are almost always seen as P Cygni profiles. Figure 1 shows the spectrum of an O star from 1000 to 8000 Å, obtained by combining low dispersion IUE data with KPNO IRS data. The P Cygni profile shape depends mainly on the mass loss rate, the velocity of the material as a function of radius, and the change in ionization with radius. More specifically, the strength of the blueshifted absorption indicates the column density of the ion, which is more or less independent of the velocity law. The ratio of emission to absorption, on the other hand, indicates the shape of the velocity law, which more or less independent of the ion column density. The reason for this is that UV resonance lines are primarily scattering lines, so the ratio of emission to absorption depends on the distance of the absorbing material from the stellar photosphere, and hence the velocity law.

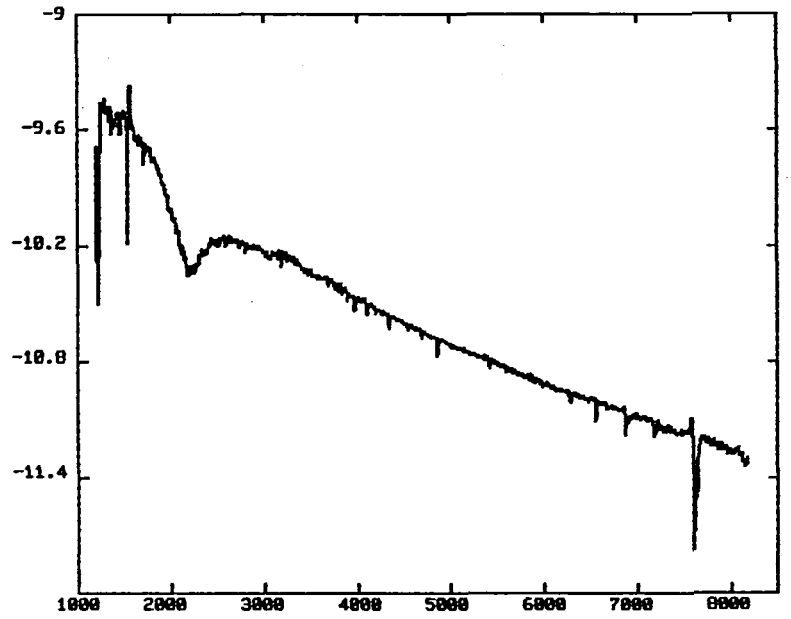

Fig. 1. The spectrum of 9 Sgr, O4V, obtained by combining an IUE low dispersion and a KPNO IRS spectrum. No correction has been made for reddening (Torres, unpublished).

The most widely accepted explanation for these winds is the line radiation pressure model, originated by Lucy and Solomon (1970) and developed further by Castor, Abbott and Klein (1975, hereafter CAK). The envelope of the star is accelerated by momentum transfer from photons to ions due to line absorption. Abbott (1982) has shown that there are sufficient lines in the UV near flux maximum to drive the wind. There are, as would be expected from an initial theory, problems to be addressed. One of the earliest was the source of the anomalously high ionization stages of O VI and N V observed in these stars. Therefore, Cassinelli and Olson (1979) proposed a "corona + cool wind" model, postulating X-rays from the base of the corona as a source of this superionization via the Auger effect. The Einstein satellite observations (Harnden et al. 1979) of X-rays from almost all early stars provided a qualitative confirmation.

A different approach was taken by Lamers and Morton (1976) who proposed that, in addition to line radiation pressure, mechanical energy from the photosphere heats the gas to the required 2×10^5 K in OB stars and produces O VI by collisional ionization. Underhill (1983) has proposed an alternative theory in which the stellar winds are generated in the "mantle," which she describes a low density region and a high density region in suspended magnetic loops of very hot gas which corotate with the star.

MASS LOSS RATES

Line profile models have been computed by Castor and Lamers (1979), and modifications provided by Olson (1981) for excited lines. Although fitting the profiles to the data does not presuppose the mechanism for accelerating and driving the wind, the ionization fraction assumed for the mass loss determination does. This is still an area of some controversy. As luck would

have it, we seldom observe the dominant stage of ionization in the winds of early stars, which are N IV, Si V and C V (Olson and Castor 1981). To compute the ionization balance, it is necessary to observe two lines on different sides of the dominant ion, such as N V and C IV. Olson and Castor find that the wind temperature is about the same for all O stars, implying that the fraction of N V is relatively constant also. On the other hand, Lamers and Snow (1978) calculate the ionization balance for N V and find enormous changes with temperature. This leads to a rather different regime in which the P Cyg lines can be used as mass loss predictors.

Ideally, one would like to compare mass loss determinations from different methods to resolve this issue. This is not easily done, however. Radio observations of free-free emission are the most model independent, depending only on the stellar distance and its flux (Wright and Barlow 1975). They can only be used for stars with the highest mass loss rates, which are generally those with saturated absorption profiles in the UV. Infrared observations of continuum free-free emission have been tried, but recent work by Castor and Simon (1983) and Abbott, Telesco and Wolff (1984) have shown that this method is unreliable. The problem lies in the assumed velocity law, which they find varies greatly from star to star.

There are two basic approaches to understanding the mechanism behind the mass loss. One is to correlate the rates with stellar characteristics such as luminosity, mass, radius, surface gravity, and rotation; the other is to study the wind structure. The underlying question is whether the winds are determined by fundamental stellar parameters or by surface phenomena. Any attempt to correlate mass loss with other stellar parameters requires careful attention to the accuracy of all the parameters involved. The earliest results showed a strong dependence on luminosity, as predicted by the radiation driven wind theory. As more data have accumulated, a variety of studies have explored additional dependences. At present, UV mass loss rates are available for about 100 O and B stars, radio rates for about 15, and IR observations for about 75 stars. This is an important advance over 5 years ago, when the numbers were about a factor of 10 smaller.

Table 1 compares some of the different dependences on mass loss, both theoretical and empirical. In a comprehensive review of the theory of line driven winds, Abbott (1982) has predicted the dependence of mass loss on luminosity, mass, temperature, and metallicity. One of the first quantitative studies of mass loss as a function of more than luminosity alone was by Lamers (1981) who scaled rates from UV, Hα and IR to radio rates. This gave a reasonable range in mass and radius, but questions have been raised about the IR rates. Lamers tried two approaches: mass loss controlled by the star's internal structure vs. mass loss as a surface phenomena; but he could find no clear indication that one was to be preferred over the other. Garmany and Conti (1984) have used a more homogeneous set of data than Lamers, and found no clear improvement from additional parameters, although they note the possibility of an empirical parameterization including the ratio of terminal to escape velocity. This is an area of tantalizing uncertainty: although second-order dependences seem to be present, the errors are large.

Table 1: Mass Loss Parameterization Coefficients

Luminosity	Radius	Mass	$M(1-\Gamma)$	$R/M(1-\Gamma)$	v_∞/v_{esc}	Metal.	Ref.
1.98			-1.03			0.94	1
1.5	2.25	-2.25					2
1.4±0.4	0.6±.1	-1.0±1.0					3
1.7±0.1				0.7±0.1			4
1.6±0.2							5
1.3±0.2					1.2±0.5		5
1.0±0.8	0.8±0.6	0.6±1.2					5

1: Abbott (1982); 2: Andriesse (1979); 3: Lamers (1981); 4: Chiosi and Olson (1984); 5: Garmany and Conti (1984).

An important independent step toward resolving the basic question of how the UV (or wind) spectra are related to fundamental stellar parameters is Walborn's classification of UV spectra (Walborn and Panek 1984b) The large body of IUE data enabled them to select 120 O and early B stars with accurate optical spectral classification and address the question: to what degree do the UV spectra correlate with their optical spectral type? They conclude that both photospheric lines, mainly Fe V and Fe IV, and wind lines, N V and C IV, are very well correlated with the optical spectral type. The implication here is that stellar wind is governed by fundamental stellar parameters.

A very interesting luminosity dependence of the Si IV profile has also been discussed by Walborn and Panek (1984a). They point out that the P Cyg profile of λ1393, 1402 develops from a pure photospheric profile in the main sequence stars to a strong wind profile in the supergiants (see Fig. 2). This has important implications both as a classification criterion and as an astrophysical problem. While C IV and N V are mostly indicative of the wind temperature, Si IV, with an ionization potential near the He II edge, is much more sensitive to the photospheric radiation field. Since there is no way to compute its ionization fraction, it cannot be used to measure mass loss as are other resonance lines. It is interesting to note that the strength of this profile is related to the surface area mass loss. In Fig. 2, the mass loss per unit area for the O6.5I star is three times that of the O6.5V star.

Winds in the Magellanic Clouds

With IUE it is an easy matter to obtain low dispersion spectra of O and luminous B stars in the Magellanic Clouds. With their lower metallicity, the Clouds offer an excellent contrast with galactic stars. If winds in the Clouds are due to radiation pressure, rates of mass loss should be smaller because CNO abundances are lower, and at least among the O stars, these are the driving lines (Abbott 1982). Alternatively, if mass loss is driven by other mechanisms but accelerated by radiation pressure, we expect the same mass loss rates but smaller wind velocities. Hutchings (1982) has discussed some of the most luminous stars in the LMC and SMC and concluded that their

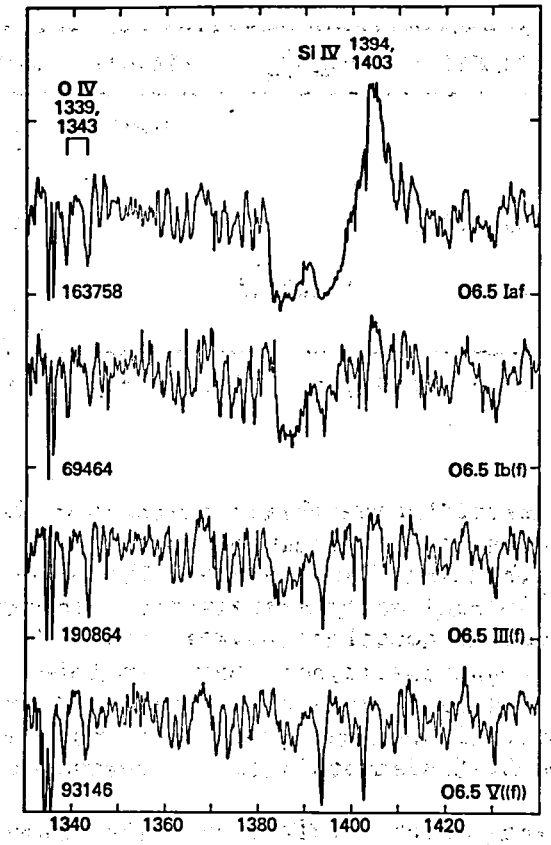

Fig. 2. The development of the Si IV P Cygni profile with luminosity (Walborn and Panek).

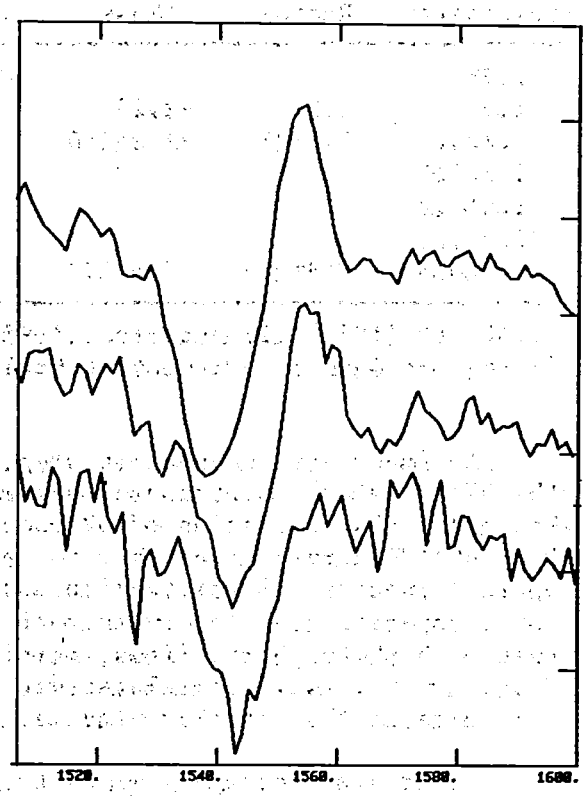

Fig. 3. The C IV line in three O7 III stars. Top: HD 151515 (Galactic), middle: SK-67°38 (LMC), bottom: AV296 (SMC).

wind velocities are lower than in corresponding galactic stars. A similar effect in the SMC alone has been noted by Bruhweiler, Parsons and Wray (1982). One prime difficulty in such studies is the lack of good spectral types for "normal" early stars in the Magellanic Clouds. As a result, many of the stars obsrved with IUE have been classified on the basis of their photometry.

Conti, Massey and I have a program to determine the initial mass function of the O stars in the Clouds, and we are observing O and B stars at classification dispersion with the 4-meter telescope at CTIO. I have observed a number of these stars with IUE and have several preliminary conclusions. The first is that photometry as a means of classifying O stars is not very reliable. An example of this can be seen in Bruhweiler et al., where photometric classification led to the comparison of a galactic O6 star with a Be star, or an O9Ia with a B3I. When we examine spectroscopically similar types, the terminal velocities do not differ very much (Fig. 3). Determining actual mass loss rates is not as straightforward. The modeling techniques used with high dispersion cannot be used on low dispersion spectra, so we must resort to other less accurate mass loss indices, such as the absorption equivalent width suggested by Snow (1979) or the first moment of the profile (Castor, Lutz and Seaton 1981). Comparing these techniques with mass loss determinations from

high dispersion spectra for the same stars shows that the simple method rapidly breaks down as the line approaches saturation. Nevertheless, we can compare the galactic, LMC and SMC stars with low mass loss rates. It appears that there is not much difference between these stars, an unexpected conclusion which we do not yet understand.

WIND STRUCTURE

The study of the structure of the stellar winds is another approach to understanding the mechanism of mass loss. This includes the velocity law, the detection of X-rays from these stars, variability in the wind profiles, and the curious absorption components seen in the wind lines. Many of these observations suggest instabilities in the wind which any theory must explain.

Wind acceleration

The wind terminal velocity, which is easily measured from the shortward edge of the strong wind lines, ranges from 1 to 3 times the stellar escape velocity. Figure 4 shows the ratio of terminal to escape velocity as a function of spectral type, taken from Cassinelli and MacGregor (1983) with additional data from Garmany et al. (1981), and Garmany and Conti (1984). The evolutionary stage of the star is indicated, and it appears that this ratio evolves with the star. Note a selection effect: later than O9 the terminal velocity is not measurable from the P Cygni profile in main sequence and giant stars. The wind theory predicts a relation between the terminal and escape velocity of the form:

$$V_\infty = \left(\frac{\alpha}{1-\alpha}\right)^{1/2} V_{esc} \quad .$$

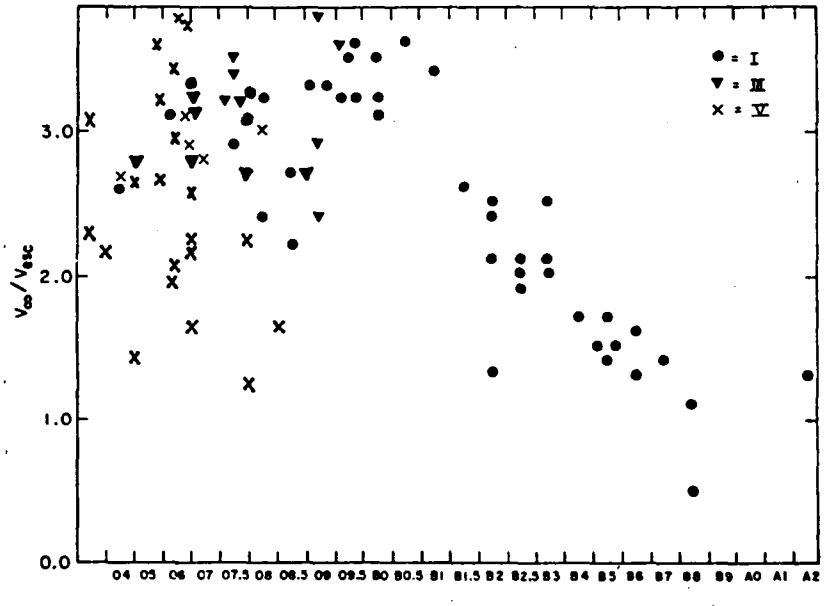

Fig. 4. The ratio of terminal to escape velocity for early type stars of different luminosity classes (adapted from Cassinelli and MacGregor).

The value of α is calculated from the relative contribution of optically thick and thin lines. Abbott (1982) found α to be constant over a broad temperature range and therefore predicted that the winds of OBA stars should conform to a relation $V_\infty = (1.0 - 1.5)\ V_{esc}$. To explain the discrepancy, especially for early O stars, Panagia and Macchetto (1981) have derived a multiphoton scattering model in which $V_\infty \propto T_{eff}^2$. Single photon scattering is sufficient for B supergiants, but multiple scattering is required to explain the observed V_∞ in O supergiants. A more complete calculation has been done by Friend and Castor (1983), who consider randomly spaced overlapping lines and conclude that the terminal velocity is much larger than in the CAK model.

Additional evidence for an evolution of the stellar wind has been found by Abbott, Bohlin and Savage (1982) who pointed out that the ratio of emission to absorption equivalent widths are a factor of 2 smaller in main sequence than in supergiant stars. This indicates a change in the shape of the velocity law in the sense that the material is farther from the star in supergiants than in main sequence stars. A changing velocity law is probably responsible for past inconsistencies between IR mass loss determinations and other methods, since the IR rates are sensitive to the assumed law. The type of velocity law that has been found to fit UV and optical line profiles as well as the IR excess is one of the form:

$$V(r) = V_\infty(1-R_*/r)^\beta$$

where β is generally assumed to be between 0.5 and 2.0. Abbott, Telesco and Wolff (1984) have investigated the problem for stars with both IR and radio observations. They see a trend for the velocity law to become more gradual (β increases) as the temperature decreases, although in their data, this could as easily represent gravity decreasing.

X-rays

That X-rays would be observed coming from O and B stars was predicted by Cassinelli and Olson (1979), who had postulated their existance to explain the anomalously high ionization stages of O and N in terms of Auger ionization. In their model, the X-rays were produced at the base of the corona and the predicted spectrum included little flux below 1 keV. Einstein IPC observations (Cassinelli et al. 1981) confirmed that O and luminous early B stars are X-ray emitters, but there exists significant flux below 1 keV. A number of explanations have been put forth. Most recently, Lucy (1982) has proposed that the X-rays are produced by shocks throughout the wind which result from instabilities in the radiation-driven wind. Cassinelli and Swank (1983) have used the Einstein SSS to make X-ray observations of the belt stars of Orion which fit Lucy's model with X-rays produced by radiation driven shocks. Lucy's theory is attractive because it also explains the broad, deep absorption troughs observed in saturated P Cygni profiles, but not in the atlas of theoretical line profiles computed by Castor and Lamers (1979). In addition, it offers a possible explanation for the narrow absorption components often seen in the wind lines, and discussed in the next section.

Based on the observation of superionized lines of C IV and Si IV in B supergiants, Odegard and Cassinelli (1982) predict that these stars should show considerable X-ray flux, with $L_x/L_{bol} \sim 10^{-8.5}$.

Line Structure and Variability

It was first pointed out by Snow and Morton (1976) from a survey of Copernicus data that the wind lines often show structure. Variously called "narrow components," "shell absorption features," "shell components," and "narrow lines" by different authors, the problem with nomenclature seems to reflect the problem in interpretation. Lamers, Gathier and Snow (1982) have described them more fully: typically they have widths of 100 to 500 km s^{-1}, small compared to the terminal velocity of -1000 to -3000 km s^{-1} of the parent star (see Fig. 5). About 2/3 of the stars in the Lamers et al. sample showed such lines, and about half the 53 stars in a study by Abbott, Bohlin and Savage (1982) had them. Since in most cases there are a small number of observations per star, it is not clear whether a certain percent of the stars show this feature, or whether all stars show these lines a certain percent of the time.

Many types of variability have been reported in early-type stars, and we do not understand how the observations are related. Historically, the Be stars are best known for showing variations in their hydrogen line profiles, although Barker (1983) notes that in a monitoring program, most did not show changes. Perhaps the best known Be star, γ Cas, has been shown by Henrichs et al. (1983) to show narrow components in 2/3 of his 28 IUE spectra. He has proposed that the narrow components represent a time dependent effect of episodic mass loss which is present in all early-type stars. Peters (1982) has also reported variations of this type in other Be stars. Such studies have only been done in a limited way for O stars. The main difference between the O and B stars seems to be that in O stars, the narrow components,

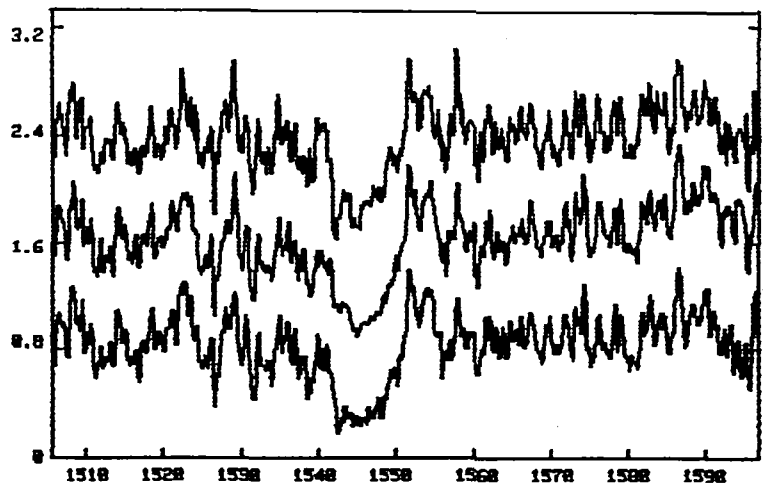

Fig. 5. IUE archive spectra of Zeta Per, B1 Ib, which shows narrow components in C IV whose strength varies with time.

while varying in strength, are fixed in velocity. Variations in the entire P Cygni profile have been observed in some O stars (Grady, Snow and Timothy 1983). Although no short-term variability was found during simultaneous UV and X-ray observations of two OB supergiants by Cassinelli et al. (1983), Snow, Cash and Grady (1981) noted long-term X-ray flux changes in a few stars. In the radio region, Abbott, Bieging and Churchwell (1981) found changes within a timescale of months.

CONCLUSION

Our knowledge of the physics of stellar winds has grown tremendously since the launch of IUE, and we are still far from exploiting the potential of the archival material. The observations have provided food for theoreticians, and although progress has been made, more work is needed.

There is at present no comprehensive theory to explain profile variability. Should we expect the same processes to be at work in an O star and a Be star? Doazan (1982) has discussed evidence for Be stars representing a phase in the life of a B star, so perhaps we should look for a similar phase in O stars. An area in which data are woefully lacking is simultaneous observations in different spectral regions. These would help to define the nature of the profile variations: for example, Gry, Lamers and Vidal-Madjar (1984) predicts Hα variations corresponding to the changes they observed in the narrow components of the Lyman lines if it represents non-symmetric mass loss. Another test would be more simultaneous UV and X-ray observations: if the X-rays are produced at the base of the wind, then X-ray variation should correspond to changes in the absorption profile, while shocks in the outer part of the wind should affect the high velocity part of the profile, including the narrow components (Lucy 1982).

Refinements in the techniques for computing mass loss would allow unambiguous comparisons with the parameterizations predicted by theory. This will require more sensitive profile modeling, as well as a better understanding of the star's fundamental parameters. The potential information from IUE observations of hot stars in the Magellanic Clouds and other galaxies is tremendous. The exposure times with the 0.5-m IUE telescope are comparable to visual observations with a 4-m ground-based telescope, and we are now moving away from studying stars or galaxies, to stars in galaxies.

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